Detecting top-Higgs at high energy e^+e^- colliders

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Abstract

We calculate the contributions of the top-Higgs h_t^0 predicted by topcolor assisted technicolor(TC2) models to $e^+e^- \longrightarrow \bar{t}c\bar{\nu}_e\nu_e$ and compare the results with the contributions of h_t^0 to the processes $e^+e^- \longrightarrow Zh_t^0 \longrightarrow Z\bar{t}c$ and $e^+e^- \longrightarrow \gamma h_t^0 \longrightarrow \gamma\bar{t}c$. We find that $e^+e^- \longrightarrow \bar{t}c\bar{\nu}_e\nu_e$ is very sensitive to h_t^0, which can be easy detected via this process at high-energy e^+e^- collider(LC) experiments with $\sqrt{s} \geq 500\,GeV$, as long as its mass below the $\bar{t}t$ threshold. The process $e^+e^- \longrightarrow \gamma\bar{t}c$ also can be used to detect h_t^0 at LC experiments.

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An important issue in high-energy physics is to understand the mechanism of the mass generation. The top quark, with a mass of the order of the weak scale, is singled out to play a key role in the dynamics of the electroweak symmetry breaking (EWSB) and flavor symmetry breaking. There may be a common origin for EWSB and top quark mass generation. Much theoretical work has been carried out in connection to the top quark and EWSB. The topcolor-assisted technicolor (TC2) models[1], the top see-saw models[2] and the flavor universal coloron models[3] are three of such examples. Such type of models generally predict a number of scalars with large Yukawa couplings to the third generation. For example, TC2 models predict the existence of the top-pions ($\pi_t^{\pm}$,π_t^0) and the neutral CP-even state, called top-Higgs h_t^0, which is analogous to the σ particle in low energy QCD. These new particle are most directly related to the EWSB. Thus, studying the possible signatures of these new particles at high energy colliders would provide crucial information for the EWSB and hopefully fermion flavor physics as well.

It is well known that there is no flavor changing neutral current (FCNC) at tree-level in the standard model (SM). The production cross section of the FCNC process is very small at one-loop level due to the unitary of CKM matrix. Thus, the FCNC process can be used to search for new physics. Any observation of the flavor changing coupling deviated from that in the SM would unambiguously signal the presence of new physics. For TC2 models[1], the underlying interactions, topcolor interactions, are non-universal and therefore do not possess a GIM mechanism. The scalars predicted by this kind of models can induce the flavor changing scalar couplings and give distinct new flavor mixing phenomena which may be tested at both low and high energy experiments[4, 5]. In this paper, we calculate the contributions of the top-Higgs h_t^0 to the t-channel vector boson fusion process $e^+e^- \longrightarrow W^+W^-\overline{\nu}_e\nu_e \longrightarrow \bar{t}c\overline{\nu}_e\nu_e$ and compare with the contributions of h_t^0 to the processes $e^+e^- \longrightarrow Zh_t^0 \longrightarrow Z\bar{t}c$ and $e^+e^- \longrightarrow \gamma h_t^0 \longrightarrow \gamma\bar{t}c$. Our results show that the top-Higgs h_t^0 can give significantly contributions to the process $e^+e^- \longrightarrow \bar{t}c\overline{\nu}_e\nu_e$ which can be detected at the high-energy e^+e^- colliders (LC) with the center-of-mass energy $\sqrt{s} = 500 - 1500\ GeV$, as long as its mass is below $2m_t$. The effects of h_t^0 on the process $e^+e^- \longrightarrow \gamma\bar{t}c$ also can be detected at the LC experiments.

According the idea of the TC2 models, there is the following relation:

$$\nu_\pi^2 + F_t^2 = \nu_w^2, \tag{1}$$

where ν_π represents the contributions of the TC or other interactions to the EWSB, $F_t \simeq 50\ GeV$ is decay constant of the scalars (top-pions or top-Higgs) predicted by the TC2 models, and $\nu_w = v/\sqrt{2} \simeq 174\ GeV$. Thus, the majority of masses of gauge bosons W and Z come from the technifermion condensate. The couplings of the top-Higgs h_t^0 to the electroweak gauge bosons W and Z at tree level are suppressed by the factor F_t/ν_w with respect to that of the SM Higgs H:

$$h_t^0 WW : \frac{F_t}{\nu_w} g m_W g_{\mu\nu}, \quad h_t^0 ZZ : \frac{F_t}{\nu_w} \frac{g m_Z}{\cos\theta_w} g_{\mu\nu}. \tag{2}$$

The couplings of the top-Higgs h_t^0 to the third generation quarks, including the $t-c$ transition, can be written as[1, 4]:

$$h_t^0 \bar{t} t : \frac{m_t}{\sqrt{2} F_t} \frac{\sqrt{\nu_w^2 - F_t^2}}{\nu_w} K^{tt}, \quad h_t^0 \bar{t} c : \frac{m_t}{\sqrt{2} F_t} \frac{\sqrt{\nu_w^2 - F_t^2}}{\nu_w} K^{tc}, \quad h_t^0 \bar{b} b : \frac{m_b^*}{\sqrt{2} F_t} \frac{\sqrt{\nu_w^2 - F_t^2}}{\nu_w}. \tag{3}$$

m_b^* is the part of the bottom quark mass generated by instanton effects, which we assume $m_b^* = 0.8 m_b$. It has been shown[4] that $K^{tt} = 1 - \epsilon$ and $K^{tc} = \sqrt{(K_{UR}^{tc})^2 + (K_{UL}^{tc})^2} \simeq K_{UR}^{tc} \leq \sqrt{\epsilon - \epsilon^2}$, which ϵ is a model dependent parameter. In this paper, we assume that the part of the top quark mass generated by the topcolor interactions makes up 99% of m_t, i.e. $\epsilon = 0.01$ and take the parameter K^{tc} as a free parameter.

The couplings of the top-Higgs h_t^0 to gauge boson pairs gg, $\gamma\gamma$ or $Z\gamma$ are similar to those of the neutral top-pion π_t^0 which come from the top quark triangle loop. The general form has been given in Ref.[5,6]. Thus, for $200 GeV \leq m_{h_t} \leq 400 GeV$, the total decay width Γ mainly comes from the decay modes $b\bar{b}$, $\bar{t}c$, WW, ZZ, gg and $t\bar{t}$ (if kinematically allowed).

The process $e^+e^- \longrightarrow \bar{t}c\bar{\nu}_e\nu_e$ can be well approximated by the W^+W^- fusion process: $W^+W^- \longrightarrow \bar{t}c$. It has been shown[7] that the effective W-boson approximation (EWA) provides a viable simplification for high energy processes involving W^+W^- fusion. Thus, we use the effective EWA to calculate the contributions of the top-Higgs h_t^0 to the process

$e^+e^- \longrightarrow \bar{t}c\overline{\nu_e}\nu_e$ and discuss the observability of h_t^0 at the LC experiments with $\sqrt{s} = 500GeV - 1500GeV$.

The production cross section of the subprocess $W^+_{\lambda_+}W^-_{\lambda_-} \longrightarrow \bar{t}c$ generated by the top-Higgs h_t^0 can be written as:

$$\widehat{\sigma}(W^+_{\lambda_+}W^-_{\lambda_-} \longrightarrow \bar{t}c) = \frac{N_c\alpha}{4S_w^2}\frac{\nu_w^2 - F_t^2}{\nu_w^4}(K^{tc})^2|\epsilon^{W^+}_{\lambda_+}\cdot\epsilon^{W^-}_{\lambda_-}|^2\frac{m_W^2m_t^2}{(\widehat{s}-m_{h_t}^2)^2+m_{h_t}^2\Gamma^2}\cdot\frac{\beta_t^4}{\beta_W}, \quad (4)$$

with

$$\beta_t = \sqrt{1-\frac{m_t^2}{\widehat{s}}}, \qquad \beta_W = \sqrt{1-\frac{4m_W^2}{\widehat{s}}}. \quad (5)$$

Where Γ is the total width of h_t^0 and $\sqrt{\widehat{s}}$ is the center-mass-energy of the WW center-mass frame. Due to a severe CKM suppression, the cross section $\widehat{\sigma}(W^+_{\lambda_+}W^-_{\lambda_-} \longrightarrow \bar{t}c)$ is very small in the SM: $\sigma_{SM}^{\bar{t}c\overline{\nu}\nu} \sim 10^{-5} - 10^{-4}$fb for $\sqrt{s} = 500 - 2000GeV$[8]. Thus, in above formula, we have neglected the SM contributions.

The cross section $\sigma^{\bar{t}c\overline{\nu}\nu}$ of the process $e^+e^- \longrightarrow \bar{t}c\overline{\nu}_e\nu_e$ can be obtained by folding the cross section $\widehat{\sigma}(W^+_{\lambda_+}W^-_{\lambda_-} \longrightarrow \bar{t}c)$ with the distribution functions $f^W_{\lambda_i}$.

$$\sigma^{\bar{t}c\overline{\nu}\nu} = \sum_{\lambda_+,\lambda_-}\int\int dx_+dx_-f_{\lambda_+}(x_+)f_{\lambda_-}(x_-)\widehat{\sigma}(W^+_{\lambda_+}W^-_{\lambda_-} \longrightarrow \bar{t}c), \quad (6)$$

where the helicities $\lambda_\pm$ of the $W^\pm$ each run over 1, 0, -1. $f_{\lambda_+}(x_+)$ and $f_{\lambda_-}(x_-)$ are the distribution functions of W^+ and W^-, respectively. Similarly to Ref.[8], we use the full distribution functions given by Ref.[7] and include all polarizations for the W boson in our calculations.

In Fig.1, we plot the cross section $\sigma^{\bar{t}c\overline{\nu}\nu}$ as a function of m_{h_t} for $\sqrt{s} = 500GeV$ and four values of the parameter K^{tc}. From Fig.1 we can see that $\sigma^{\bar{t}c\overline{\nu}\nu}$ increases with increasing the value of K^{tc} and reach the maximum value for $m_{h_t} = 215GeV$. For $m_{h_t} > 2m_t$, the $\sigma^{\bar{t}c\overline{\nu}\nu}$ drops considerably since the $\bar{t}t$ channel opens up and the branching ratio $B_r(h_t^0 \longrightarrow \bar{t}c)$ drops substantially. If we assume that a yearly integrated luminosity of a LC experiment with $\sqrt{s} = 500GeV$ is about $50fb^{-1}$, then the cross section $\sigma^{\bar{t}c\overline{\nu}\nu}$ would yield several tens to hundreds such events in most of the parameter space (m_{h_t},K^{tc}). For example, for $m_{h_t} = 300GeV$ and $K^{tc} = 0.05$, there would be 25 such events to be generated at the LC experiments with $\sqrt{s} = 500GeV$.

It is well known that, for high energy process involving W^+W^- fusion, the corresponding cross section grows with the center-mass-energy $\sqrt{s}$ of colliders. To see the effects of $\sqrt{s}$ on the production cross section, we plot the cross section $\sigma^{\bar{t}c\bar{\nu}\nu}$ versus m_{h_t} in Fig.2 for $K^{tc}=0.05$ and four values of $\sqrt{s}$. The cross section increases from $1.24fb$ to $9.97fb$ as $\sqrt{s}$ increases from $500GeV$ to $1500GeV$ for $m_{h_t}=250GeV$. It is evident from Fig.2 that the top-Higgs h_t^0 would produce several hundreds to thousands of $\bar{t}c\bar{\nu}_e\nu_e$ events in a LC running at $\sqrt{s}\geq 1000GeV$ with an integrated luminosity of $L\geq 100fb^{-1}$. Thus, it is very easy to detect the signals of h_t^0 via this process at a LC experiment with $\sqrt{s}\geq 1000GeV$.

Certainly, the top-Higgs h_t^0 has contributions to the process $e^+e^-\longrightarrow \bar{t}ce^+e^-$ via the subprocess $ZZ\longrightarrow h_t^0\longrightarrow \bar{t}c$. The main difference between $\sigma^{\bar{t}c\bar{\nu}\nu}$ and $\sigma^{\bar{t}cee}$ arises from the dissimilarity between the distribution functions for W and Z bosons. Such the distribution functions of gauge boson Z are smaller than those of gauge boson W, $\sigma^{\bar{t}cee}$ is expected to be smaller by about one order of magnitude than $\sigma^{\bar{t}c\bar{\nu}\nu}$[8]. This conclusion is model independent. Thus, we do not consider the contributions of the top-Higgs h_t^0 to the process $e^+e^-\longrightarrow \bar{t}ce^+e^-$ in this paper.

The top-Higgs h_t^0 also has contributions to the process $e^+e^-\longrightarrow Z\bar{t}c$ via the Bjorken process $e^+e^-\longrightarrow Zh_t^0$ followed by $h_t^0\longrightarrow \bar{t}c$. Thus, h_t^0 may be detected via this process at the LC experiments. To compare the production rate of $e^+e^-\longrightarrow \bar{t}c\bar{\nu}_e\nu_e$ with that of $e^+e^-\longrightarrow Z\bar{t}c$ in TC2 models, we plot the rate $R_1=\frac{\sigma^{\bar{t}c\bar{\nu}\nu}}{\sigma^{Z\bar{t}c}}$ as a function of m_{h_t} for $K=0.05$ and three values of $\sqrt{s}$ in Fig.3. We find that the cross section $\sigma^{Z\bar{t}c}$ decreases with increasing the values of m_{h_t} or $\sqrt{s}$. For $\sqrt{s}\geq 500GeV$, the ratio R_1 is larger than 1 in most of the parameter space. For example, for $m_{h_t}=300GeV$, $K^{tc}=0.05$ and $\sqrt{s}=500GeV$, the ratio R_1 approximately equals to 2. Thus, it is very difficult to detect the top-Higgs h_t^0 via the process $e^+e^-\longrightarrow Z\bar{t}c$ at LC experiments with $\sqrt{s}\geq 500GeV$.

Since the top-Higgs h_t^0 can couple to gauge boson pair VV via the quark triangle loop, the top-Higgs may have significantly contributions to process $e^+e^-\longrightarrow h_t^0\gamma\longrightarrow \gamma\bar{t}c$. This has been studied in Ref.[5] for the neutral top-pion π_t^0. To see whether h_t^0 can be detected via $e^+e^-\longrightarrow \gamma\bar{t}c$, we plot the ratio $R_2=\frac{\sigma^{\bar{t}c\bar{\nu}\nu}}{\sigma^{\gamma\bar{t}c}}$ as a function of m_{h_t} for $K^{tc}=0.05$ and three values of $\sqrt{s}$ in Fig.4. From Fig.4, we can see that the cross section $\sigma^{\gamma\bar{t}c}$ increases

with $\sqrt{s}$, but its speed is smaller than that of the $\sigma^{\bar{t}c\overline{\nu}\nu}$. For $m_{h_t} = 250GeV$, $K^{tc} = 0.05$, the ratio R_2 increases from 1.08 to 4.00 as $\sqrt{s}$ increases from 500GeV to 1500GeV. For $\sqrt{s} = 500GeV$ and in the range of $200GeV \leq m_{h_t} \leq 350GeV$, $0.24 \leq R_2 \leq 1.05$. Thus h_t^0 also can be detected via the process $e^+e^- \longrightarrow \gamma\bar{t}c$ at the LC experiments.

For $m_{h_t} \leq 350GeV$, gg is one of the dominant decay modes of the top-Higgs h_t^0. h_t^0 may have significantly contributions to the top-charm production at hadron colliders. This has been extended studied by G. Burdman[4]. His results show that the cross section of the gluon fusion production and subsequent decay of the top-Higgs h_t^0 into the $\bar{t}c$ final state is very large. There will be several thousands of $\bar{t}c$ events to be generated at the LHC, which are larger than the number of $\bar{t}c\overline{\nu}_e\nu_e$ events produced at the LC experiments. Thus it is possible that the top-Higgs h_t^0 can be more easy detected at the LHC than at the LC experiments. However, we must separate the signals from the large backgrounds before observation of the top-Higgs h_t^0 at the LHC.

For TC2 models, the underlying interactions, topcolor interactions, are non-universal and therefore do not possess a GIM mechanism. The non-universal interactions result in FCNC vertices when one writes the interactions in the quark mass eigen-basis. Thus, the top-Higgs h_t^0 can induce the new flavor changing scalar coupling including the $t-c$ transitions. Considering the production ratio of the FCNC process is negligible small in the SM, we can use the FCNC process to discuss the observability of the top-Higgs h_t^0. In this paper, we calculate the contributions of h_t^0 to the processes $e^+e^- \longrightarrow \bar{t}c\overline{\nu}_e\nu_e$, $e^+e^- \longrightarrow Z\bar{t}c$ and $e^+e^- \longrightarrow \gamma\bar{t}c$ and compare the results with each other at the LC experiments with $\sqrt{s} = 500GeV - 1500GeV$. Our results show that the processes $e^+e^- \longrightarrow \bar{t}c\overline{\nu}_e\nu_e$ and $e^+e^- \longrightarrow \gamma\bar{t}c$ can be used to detect the top-Higgs h_t^0 at LC the experiments with $\sqrt{s} \geq 500GeV$. However, the process $e^+e^- \longrightarrow \bar{t}c\overline{\nu}_e\nu_e$ is more sensitive to h_t^0 than that of $e^+e^- \longrightarrow \gamma\bar{t}c$, especially in the LC experiments with $\sqrt{s} \geq 1000GeV$.

Figure captions

Fig.1: The cross section $\sigma^{\bar{t}c\overline{\nu}\nu}$ versus the top-Higgs mass m_{h_t} for the center-mass-energy $\sqrt{s} = 500GeV$ and $K^{tc} = 0.02$, 0.05, 0.08, 0.1.

Fig.2: The cross section $\sigma^{\bar{t}c\overline{\nu}\nu}$ versus m_{h_t} for $K^{tc} = 0.05$ and $\sqrt{s} = 500GeV$, $1000GeV$, $1500GeV$.

Fig.3: The ratio $R_1 = \sigma^{\bar{t}c\overline{\nu}\nu}/\sigma^{Z\bar{t}c}$ as a function of m_{h_t} for $K^{tc} = 0.05$ and $\sqrt{s} = 500GeV$, $1000GeV$, $1500GeV$.

Fig.4: The ratio $R_2 = \sigma^{\bar{t}c\overline{\nu}\nu}/\sigma^{\gamma\bar{t}c}$ as a function of m_{h_t} for $K^{tc} = 0.05$ and $\sqrt{s} = 500GeV$, $1000GeV$, $1500GeV$.

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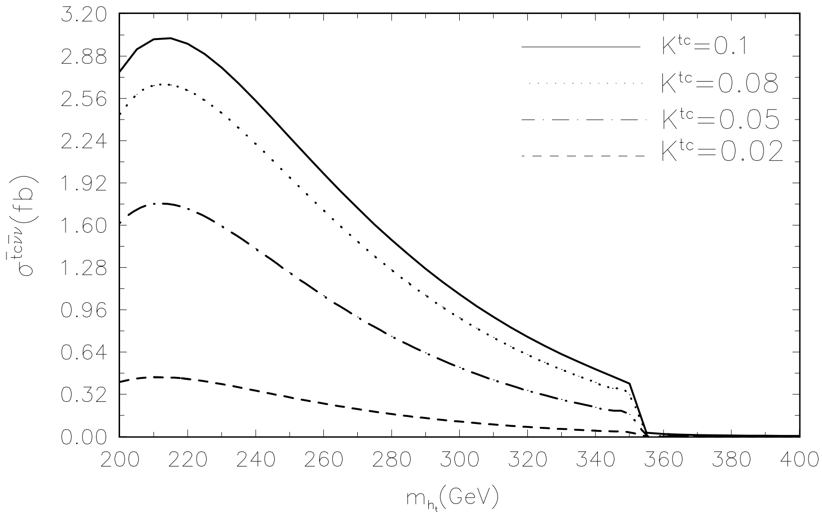
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2.56
2.24
1.92
1.60
1.28
0.96
0.64
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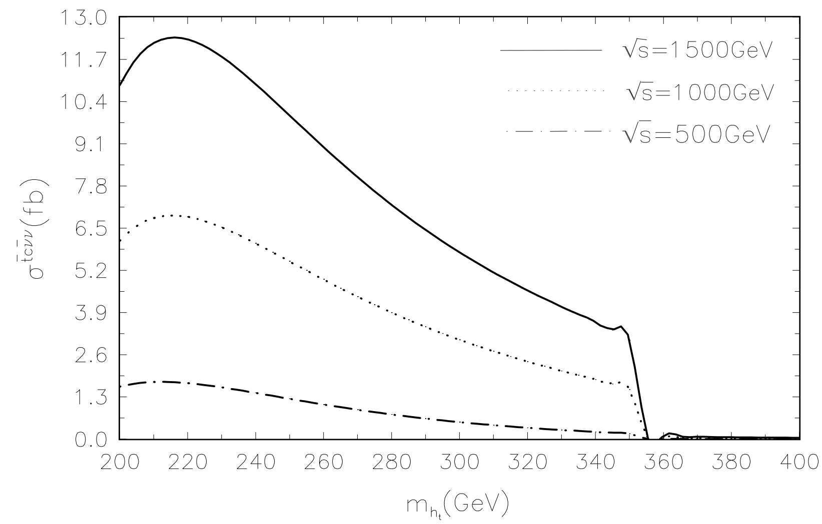
260
280
300
320
340
360
380
400
K^{tc}=0.1
K^{tc}=0.08
K^{tc}=0.05
K^{tc}=0.02
$\sigma^{\bar{t}c\bar{\nu}\nu}$(fb)
m_{h_t}(GeV)

Fig.1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11.7
10.4
9.1
7.8
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200
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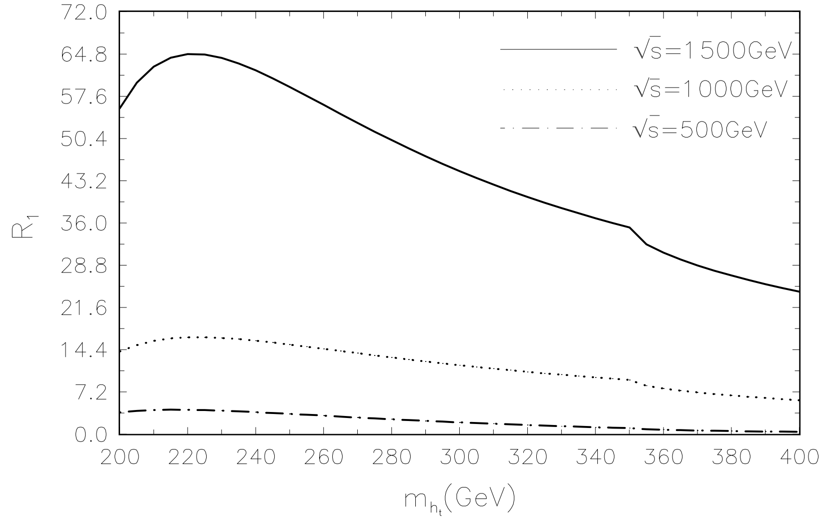
380
400
$\sqrt{s}$=1500GeV
$\sqrt{s}$=1000GeV
$\sqrt{s}$=500GeV
$\sigma^{\bar{t}c\bar{\nu}\nu}$(fb)
m_{h_t}(GeV)

Fig.2



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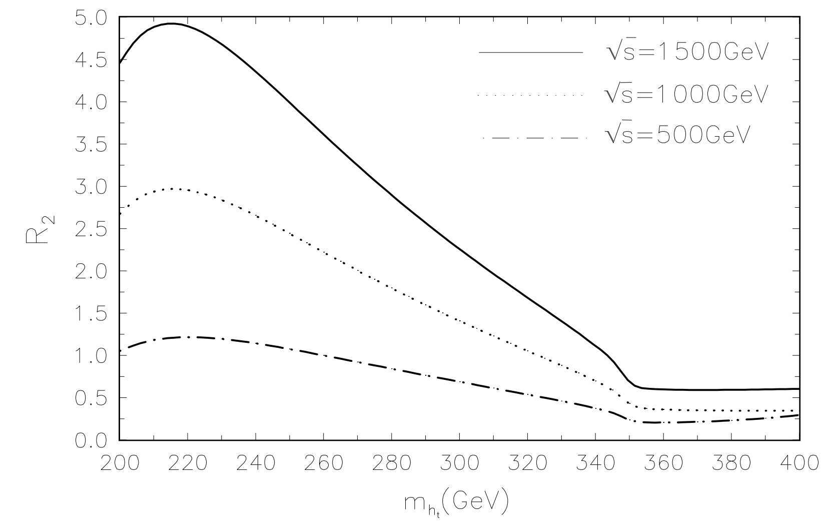
64.8
57.6
50.4
43.2
36.0
28.8
21.6
14.4
7.2
0.0
R1
200 220 240 260 280 300 320 340 360 380 400
m_{h_t}(GeV)
√s=1500GeV
√s=1000GeV
√s=500GeV

Fig.3



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4.0
3.5
3.0
2.5
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1.5
1.0
0.5
0.0
R2
200 220 240 260 280 300 320 340 360 380 400
m_{h_t}(GeV)
√s=1500GeV
√s=1000GeV
√s=500GeV

Fig.4